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The Effects of Ejection Seat Cushion Design on Physical Fatigue and Cognitive Performance

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Air Force Research Laboratory
Human Effectiveness Directorate
Biosciences and Protection Division
Biomechanics Branch
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NOTICE

TECHNICAL REVIEW AND APPROVAL

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

//signed//

MARK M. HOFFMAN
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14. ABSTRACT

The detrimental effects of prolonged sitting during long-duration flights include deep vein thrombosis, pressure sores, and decreased awareness and performance. However, the cushion is often the only component of the ejection seat system that can be modified to mitigate these effects. This study investigated the long-duration effects of sitting in four ejection seat cushions over eight hours. Subjective comfort survey data and cognitive performance data were gathered along with comparative objective data, including seated pressures, muscular fatigue levels, and lower extremity oxygen saturation. Peak seated pressures ranged from 1.22 – 3.22 psi. Oxygen saturation in the lower extremities decreased over the eight hours. Cognitive performance increased over time regardless of cushion with the exception of the dynamic cushion, which induced a decrease in performance for females. Muscular fatigue increased throughout the eight hours regardless of cushion, with the exception of the dynamic cushion which promoted muscular recovery. Subjective comfort levels declined over the eight hours. Subjective measurements correlated with objective parameters for the static cushions. Trade-offs in performance and fatigue mitigation were apparent in the dynamic cushion which also highlighted the differences between genders. These results will be used to develop cushion design guidelines, both to prevent deep vein thrombosis and to promote performance and comfort for long-duration use.

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Cushion comfort, fatigue, performance, ejection seat

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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PREFACE

The experimental tests described in this report were conducted by the Biomedical Engineering Department of Wright State University, Dayton, Ohio. Analyses of the data were accomplished by the Biomechanics Branch, Human Effectiveness Directorate of the Air Force Research Laboratory (AFRL/HEPA) at Wright-Patterson Air Force Base (WPAFB), Ohio; the Department of Work Environment, Netherlands Organization for Applied Scientific Research (TNO), Soesterberg, The Netherlands; and Wright State University (WSU).

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INTRODUCTION

The purpose of this study was to develop objective methods for determining and predicting human comfort in operational and prototype U.S. Air Force crew seat cushions. To achieve this, four main questions were addressed in this study: 1) Is there a measurable difference between cushion types in physical responses, namely seated pressures, and physiological responses, namely muscular fatigue and lower extremity oxygen saturation? 2) Is there a measurable difference in cognitive performance between cushion types? 3) Is there a measurable difference in perceived comfort between cushion types? 4) What conclusions can be drawn regarding the existing correlations of the above physical, physiological, and performance parameters with perceived comfort?

This study is part of an overall effort to define seat and cushion parameters that will maximize comfort and performance without jeopardizing ejection safety. Previous work includes a pilot study done in 1999 in which five males were monitored for a 4-hour sit duration [1]. This study indicated the need for long-duration monitoring to gain a realistic understanding of the long-term effects on the operator's responses. The pilot study also led to improvements for the first 8-hour sit duration study conducted in 2003 in which a larger, more diverse subject panel was observed on four cushion types in an F-15 seat configuration [2]. The 2003 study highlighted the correlations that exist between objective seated pressures and subjective comfort levels.

The tools and measurement techniques employed in the current effort were selected based on the results from the first two studies. The current effort expanded upon the previous studies by introducing additional variables including dynamic cushion properties, increased measurement frequencies, and new measurement techniques. These techniques included monitoring the percent change in lower extremity blood oxygen saturation levels to provide an estimation of blood flow behavior and monitoring low back and shoulder muscular fatigue. Blood pooling was selected for monitoring due to periods of minimal to no motion in the leg during long-term flight, which can lead to deep vein thrombosis (DVT). Muscular fatigue levels in the low back and shoulder were selected for monitoring due to the long-duration effects of low-level sustained contractions. Combined, these factors are suspected of being significant contributors of discomfort during seated long-term flight.

BACKGROUND

Ejection seat cushions in current U.S. Air Force aircraft are not optimized for comfort during extended missions. With combat bomber crew missions during Operation Enduring Freedom reaching over 40 hours in length, it has become increasingly important that crewmember seat comfort be improved. These improvements are critical to enhancing both physical endurance and combat effectiveness. Shortcomings of existing ejection seat cushions have been documented by researchers [3,4,5] and through interviews conducted with pilots and flight surgeons [6]. The most common complaints were buttock and lumbar spine soreness, tingling in the extremities, numbness and overall fatigue.

The discomfort experienced during extended missions has several causes. The materials used in ejection seat cushions are not selected based on their comfort properties; rather, they are selected for their performance in limiting spinal injuries during ejection. Cockpit space restrictions associated with most ejection-seat-equipped aircraft severely restrict the seat occupant's ability to reposition during flight. Ejection seat dimensions and contours are fixed, causing accommodation problems, especially for large and small occupants. Previous research has shown that all of these problems can be addressed [3,5,7]. Completely eliminating all occupant discomfort would likely require an entire seat system redesign or an imposed limitation on the duration of the mission.

A feasible component of the seat system to which cost-effective modifications can be made to enhance aircrew comfort is the ejection seat cushion. Recent studies have shown that cushions made from various densities of Confor™ provide superior impact protection and improved occupant comfort [3,4,8,9] compared to foam rubber or polyurethane combinations. In fact, a replacement cushion was approved for use in the B-2 and other ACES II configurations based upon impact testing and an evaluation of cushions with different densities of Confor™ and various surface contours. However, in a recent evaluation of the replacement B-2 cushions, it was determined that no single cushion could be designed to accommodate the entire anthropometric range. It was recommended that individual cushions be fitted for each pilot [3]. Another technique that has been used extensively for wheelchair users is active stimulation incorporated within the cushion using pulsation or vibration devices. A qualification study was performed on a pulsating seat cushion and adjustable lumbar pad combination for U.S. Navy aircraft. The results showed no increased injury risk, but also highlighted the need for further research in this area [10].

METHODS

Study Description

All tests were conducted at the Biomedical Engineering Department of Wright State University. Prior to data collection, the study plan was approved by both the Wright State University and the Wright-Patterson AFB Wright Site Institutional Review Boards. A series of long-duration comfort evaluations were conducted using human volunteer subjects on four cushion types. The four cushions consisted of an operational ACES II cushion, a prototype Oregon Aero cushion, an in-house-developed cushion consisting of Confor™ C-47 with a Soft Supracor Stimulite cover, and an Ergo Air ErgoDynamic™ Therapeutic Seating System 2000 cushion. The three former cushions were static. The latter cushion had a mechanical pumping action incorporated with the intention of dynamically stimulating blood flow while seated. Subjects completed 8-hour seated tests on each cushion on four separate days in a sequential counter balanced order. During each 8-hour session, subjects were seated in an F-16 ejection seat mockup with their feet resting on a foot pedestal. While seated, non-invasive objective measures were recorded including physical, physiological, and cognitive parameters. The physical parameters recorded were the pressures and contact areas elicited at the subject-cushion interface,

which were collected using a thin film pressure sensor mat. The physiological parameters recorded were the electromyography (EMG) of the trapezius, internal oblique and erector spinae muscles and the regional blood oxygen saturation in the lower extremities. The cognitive parameter recorded was the performance levels on a multi-attribute task battery. In addition to the objective parameters, subjective comfort evaluations were collected at 2-hour intervals during the 8-hour seated session and upon completion of the session. By measuring objective and subjective parameters, existing correlations in the two data types could be identified.

The subject-cushion interface pressure and contact area measurements of the seated surface area (buttocks, thighs, and back) were collected before each 8-hour session commenced using an XSENSOR™ X2 Pressure Imaging System (XSENSOR Technology Corporation, Calgary, Canada). The pressure mat was placed on top of the seat pan and against the back cushion. Subjects sat atop the pressure mat for 6 minutes for the operational ACES II cushion, the Oregon Aero prototype and the Stimulite/Confor™ blend cushion, and 10 minutes for the ErgoDynamic™ Therapeutic Seating System 2000. Previous studies [2] have indicated that a 6-minute settling period is sufficient time to allow the occupant and cushion to reach a steady state with no additional significant pressure fluctuations for static cushions. A pressure snapshot was recorded at the end of the 6-minute period for the static cushions. Because settling will not occur due to dynamics, a 10-minute pressure profile was recorded to capture the changes in pressure and contact area for the 10-minute cycle time of the ErgoDynamic cushion.

Electromyography data were collected using the DELSYS® MyoMonitor III data acquisition system (DELSYS INC.®, Boston, MA) for 10-second periods every 30 minutes from three pairs of EMG sensors located on the subjects' right and left trapezius, internal oblique, and erector spinae muscles. EMG data were collected while the subject continued the sitting task.

Regional blood oxygen saturation in the lower extremities was measured using an INVOS® Near-Infrared Spectroscopy Oximeter (Somanetics Corporation, Troy, MI). The sensor, a SomaSensor, was placed on the bulk of either the right or left calf muscle depending on which of two ejection seat stations the subject was seated. The SomaSensor was a flexible adhesive sensor of 1"x4" that contained no hazards to the subjects. The INVOS® Oximeter collected a steady stream of blood oxygen saturation data over the entire 8-hour session.

At the start of each session and every two hours thereafter, the subject completed a cognitive task battery as a performance measure using SynWin software. Every 30 minutes during the 8-hour tests, the subjects were required to perform isometric and leg stretching exercises to reduce the risk of deep venous thrombosis. At the beginning and every two hours thereafter, subjects completed an electronic comfort survey to document their perceived physical discomfort level. After the subjects completed the 8-hour session and stood clear of the ejection seat, a final comfort survey documenting any new discomforts was administered.

Subjects

All subjects were screened to ensure no pre-existing risk factors existed that may have increased their risk for developing deep vein thrombosis. To do so, a "Medical Prescreen Questionnaire" was administered and reviewed by a qualified medical monitor. Of 31 subjects who were medically cleared to participate, 7 were unable to complete all test sessions due to scheduling conflicts, 1 dropped out of the study due to discomfort, and 1 was medically disqualified. The data in this paper represent the 22 subjects, 9 females and 13 males, who completed all test sessions. Basic subject anthropometry is shown in Table 1.

Table 1. Subject Anthropometry

	Female (n=9)	Male (n=13)
Age (years)		
Range	21-28	22-30
Average	24.44 ± 2.46	25.69 ± 2.78
Weight (lbs)		
Range	124.25-170.13	123.25-250.25
Average	148.64 ± 18.27	190.07 ± 41.44
Height (in)		
Range	63.38-71.44	67.0-74.94
Average	66.08 ± 2.63	69.95 ± 2.58

As an indication of how closely the subject pool represented the operational height and weight range, test subject dimensions were plotted against the current U.S. Air Force Pilot size (see Figure 1).

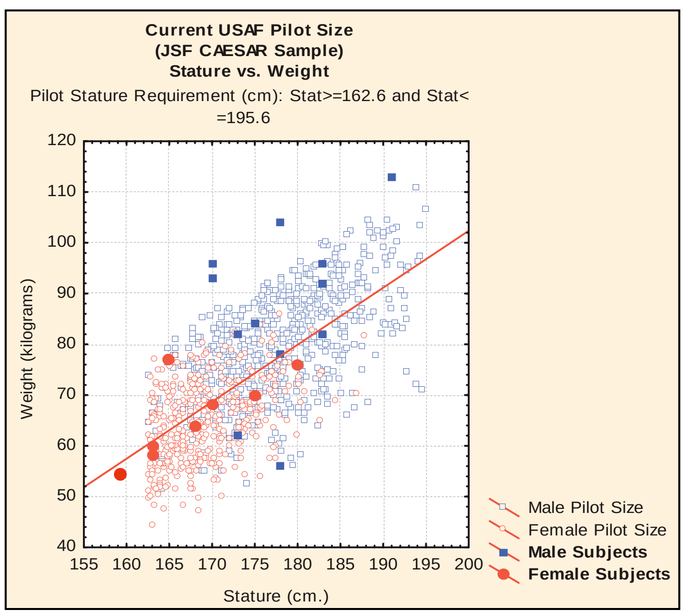


Figure 1. Test subject size plotted against U.S. Air Force pilot size

Workstations

Two workstations were constructed utilizing ejection seat mockups and foot pedestal assemblies modified to simulate the ACES II seat in the F-16 configuration as shown in Figure 2. The seat was mounted such that the rail angle was 15° aft of vertical and the seat pan was inclined 4° from the horizontal. Horizontally adjustable foot pedestals were used for all tests. The subjects were allowed to remove their feet from the foot pedestal during the session. All subjects were instructed to wear a flight helmet (HGU-55/P) during the 8-hour session. However, subjects were allowed to remove the helmet as desired. Subjects were also provided with an aircrew-type urine collection device for use when needed. Figure 2a shows one complete workstation. Figure 2b shows the workstation in use during a test session.

A B

Figure 2. a) Workstation components b) Workstation used during test session

Test Cushions

The four cushion specimens that were chosen for use in this study were selected based on their material properties and the prediction that they would provide a diverse range of objective and subjective results. Table 2 shows the four cushions, including: an operational ACES II cushion, a prototype from Oregon Aero, a cushion made in-house by combining Confor™ C-45 with a Soft Supracor Stimulite cover, and a dynamic cushion traditionally used to alleviate stresses induced by prolonged wheelchair sitting. Subjects completed one 8-hour test on each cushion. Test sessions were completed in alphabetical order of the Cushion ID with the first session selected based upon a counterbalanced study method.

Table 2. Cushion Specimens and Descriptions

Cushion	Cushion ID & Description
	Cushion A Current ACES II Cushion – Confor™ C-47 and Polyethylene with sheepskin cover
	Cushion B Oregon Aero Prototype – Contoured C-47 with sheepskin cover
	Cushion C Stimulite/Confor™ Blend – 1" C-45 with 1" soft Supracor Stimulite top layer and nylon cover
	Cushion D Ergo Air ErgoDynamic™ Therapeutic Seating System 2000 with mechanical pumping action

Test Equipment

<u>Pressure Measurement</u>

All pressure and contact area measurements were obtained using the XSENSOR™ X2 Pressure Imaging System. The system consisted of two thin mats, each containing a 36 x 36 array of sensors, a data interface cable, a data acquisition module, and PC software for data analysis as shown in Figure 3. The sensor mats are extremely thin and pliable, enclosed in a nylon covering, and conform to the shape of any surface on which they are placed. The mats were placed on top of the seat pan cushion and against the back cushion. Subjects sat directly on top of the sensor mats. Similar pressure measurement systems have been used extensively over the past decade for medical, automotive, and manufacturing pressure evaluations [11,12]. The XSENSOR™ software interface is highly user-configurable and allows for recording data over a span of time or as a still-frame snapshot in time. Subject pressure snapshots were collected at the beginning of each 8-hour test session following a 6-minute settling period for the static cushions. For the dynamic cushion, a time record of the pressure and contact area distribution was collected for the entire 10-minute air flow cycle.

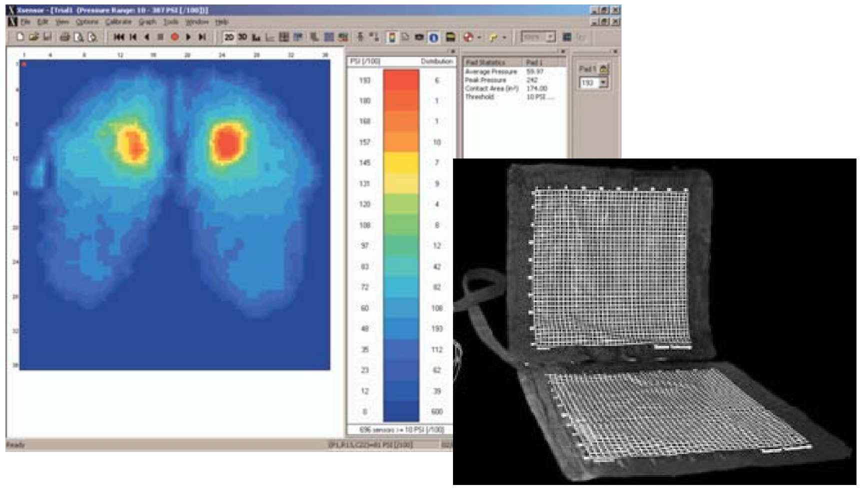


Figure 3. Pressure mats and measurement output screen

Muscular Fatigue

The median frequency of the left and right trapezius, erector spinae, and internal obliques was analyzed from the electromyography (EMG) signals that were collected using the DELSYS® hand-held Myomonitor® III data acquisition system. Muscle locations are indicated in Figure 4. The reference ground electrode was placed on the C7 cervical vertebrae. The trapezius was located by palpating the musculature between the acromion and the C7 cervical vertebrae. The electrodes were placed parallel to the muscle fibers. The internal oblique muscles were located by having the subject twist the torso. Electrodes were placed parallel to the muscle fibers that ran at a 45° angle from the lumbar spine. The erector spinae muscles were located by having the subject bend at the waist in flexion and extension. Electrodes were placed parallel to the muscle fibers. No measurable signal interference was detected due to contact between the subject's back and the back of the seat. The median frequency was used as a means to determine whether muscular fatigue in the shoulder and lumbar muscles induced by either cushion type, seated duration or both was present. The data acquisition system had the capability of acquiring eight channels of data. Six signal-conditioning surface electrodes with a contact dimension of 10 x 1.0 mm were used. The electrodes required minimal skin preparation and, after being located via palpation, muscle sites were simply cleaned thoroughly with rubbing alcohol. EMG signals from the 6 electrodes were recorded at the start of each session and every 30 minutes for 10-second durations.

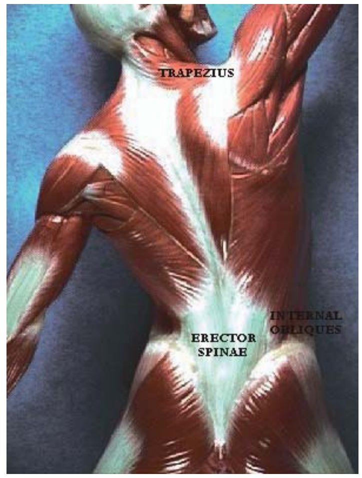


Figure 4. Muscle sites monitored via surface electromyography

Oxygen Saturation

The Somanetics Oximeter was used to collect oxygen saturation of the lower extremities while the subject was seated. The oximeter monitors continuous changes in oxygen saturation of the blood. The measurement is made by noninvasively transmitting and detecting low intensity, near infrared light through sensors that are adhered to the skin surface over the bulk of the medial head of the gastrocnemius muscle (see Figure 5). Oximeter readings were recorded continuously at a rate of 14 samples/min from the start of Hour 0 to the end of Hour 8.

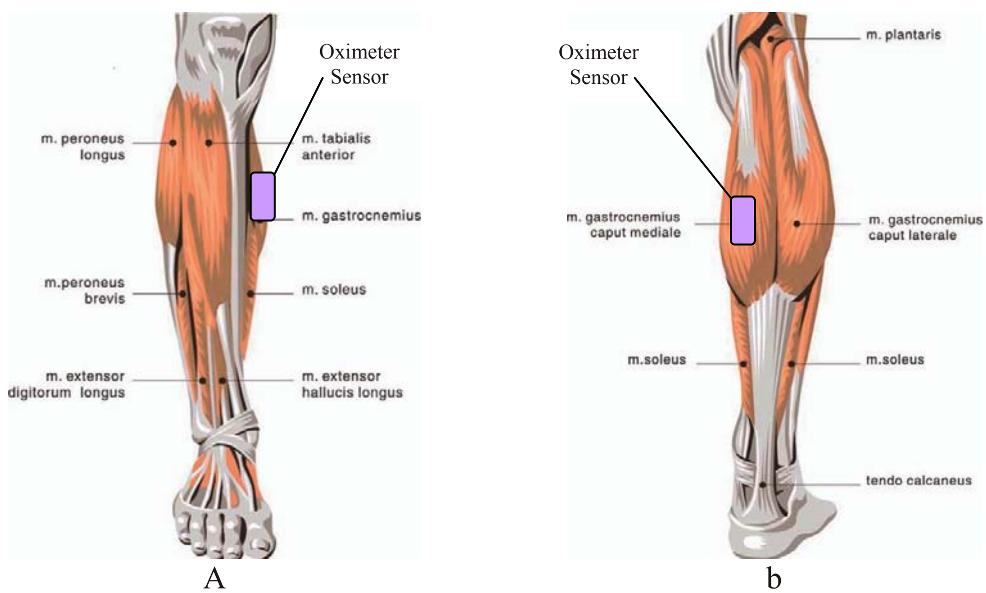


Figure 5. Oximeter placement relative to internal musculature a) anterior view b) posterior view

SynWin Cognitive Task Battery

At the start of each session and every two hours thereafter, subjects completed a 5-minute cognitive task battery as a measure of performance throughout the 8-hour session.

SynWin, created by Activity Research Services, was used to obtain objective performance data. The SynWin analysis provided a benchmark set of tasks for use in a wide range of laboratory studies of operator performance and workload and is similar to the Multi-Attribute Task Battery (MATB). The software incorporates tasks analogous to activities that aircraft crewmembers perform in flight, while providing a high degree of experimenter control, performance data on each subtask, and freedom to use non-pilot test subjects. The battery consisted of four tasks to which the subjects had to simultaneously respond. The primary display is composed of four separate task quadrants: the upper left quadrant is a memory task, the upper right quadrant is an arithmetic task, the lower left quadrant is a visual monitoring task, and the lower right quadrant is an auditory monitoring task (see Figure 6). The program reports a composite score and individual task scores for each 5-minute test. Subjects were trained on SynWin to a point where their scores reached a plateau and stabilized prior to starting their first 8-hour test session. SynWin has successfully been used as a measure of cognitive performance in a previous comfort evaluation [2] and has been used extensively by the Warfighter Fatigue Countermeasures Branch of the Air Force Research Laboratory.

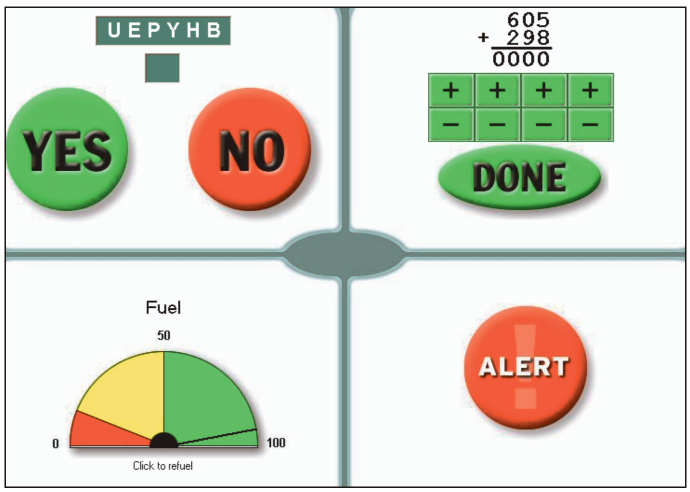


Figure 6. The four quadrant tasks comprising the SynWin task battery

Subjective Survey

Two subjective comfort surveys were completed by the subjects every test session. The first was the Seated Comfort Survey which consisted of two sections, including: 1) the physical condition measured at the start and every two hours thereafter of the whole body (referred to as "physical condition") and of individual body parts (referred to as "local postural discomfort" or "LPD" as shown in Figure 7); and 2) the general seat impressions measured at the end of the session while seated. For the first section of the Seated Comfort Survey, the physical condition was rated on a 10-point scale, ranging from 1 (bad), 4 (not well), 7 (ok), to 10 (great). The LPD was rated on a 12-point scale ranging from 0 (no discomfort), 3 (moderate discomfort), 5 (strong discomfort), 7 (very strong discomfort) to 11 (maximal discomfort). For the second section of the Seated Comfort Survey, the general seat impressions, two types of questions were included: 1) the amount of support for a certain body part (e.g., buttocks, lower back, middle leg, thighs, etc.) and 2) the amount of comfort provided by the seat for the same body part. A 7-point

scale was used for the firmness rating ranging from -3 (too weak), to 0 (OK), to +3 (too firm). A 5-point scale was used for the comfort rating ranging from 1 (uncomfortable) to 5 (comfortable).

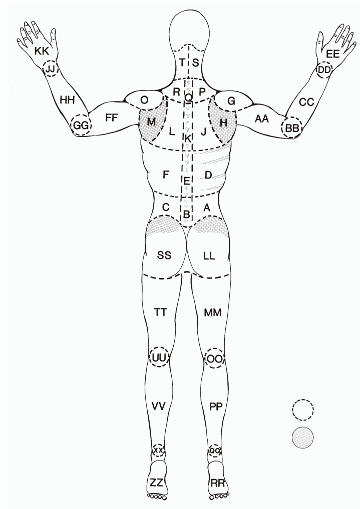


Figure 7. Body areas used for the LPD ratings

The second subjective comfort survey was the End-of-Day Comfort Survey, which was administered at the end of the 8-hour session after the subject stood up out of the ejection seat. This survey required the subjects to rate on a 12-point scale the discomfort, hot spots, or numbness of 11 body parts that became noticeable once they stood up. Both surveys were collected to compare the subjective comfort ratings to objective data.

Test Session Sequence

<u>Initial Session</u>
Initial focus was on subject familiarization with and training on the SynWin Cognitive Task Battery. Subjects were trained for up to two hours on the use of the SynWin software. Test conductors determined when subjects were knowledgeable with the software. Subjects were considered adequately trained on the SynWin software when they reached an improvement plateau (i.e., they did not get any better at the task no matter how many times they performed it). Subjects were required to run at least 10 five-minute trials, unless they exhibited mastery of the software and reached a plateau before the 10 trials were completed. In addition, subjects were shown how to complete the electronic comfort survey and were allowed to practice on the survey until they felt comfortable utilizing it.

<u>8-Hour Session</u>
The test conductor informed the subjects of the tasks and procedures. The subjects were prepped for and fitted with EMG and oximeter sensors. Seat pan and back rest pressure mats were placed directly atop the test ejection seat cushion. The subjects were seated for a 6- or 10-minute settling period, depending on the cushion type, on the pressure mat and pressure measurements were collected. The pressure mats were then removed, which

marked the beginning of the 8-hour seated session. The oximeter data were started and continuously recorded until the end of the 8 hours. EMG data were collected for 10 seconds at time 0 and every 30 minutes thereafter. Additionally, at time 0, the first SynWin cognitive task session and the Seated Comfort Survey were administered; this was repeated at 2, 4, 6 and 8 hours. During each 8-hour test, subjects were instructed to complete basic isometric and stretching exercises for the legs every 30 minutes to mitigate the risk of deep venous thrombosis from prolonged periods of static seating. Subjects remained seated at all times during the 8-hour tests. Subjects were trained on the use of appropriate bladder relief devices, which were utilized as needed. At the end of the 8 hours, the oximeter data collection was terminated and, once the subject stood up, the End-of-Day Survey was completed.

Data Analysis

From the pressure recordings, the measurements of interest included average pressure, peak pressure and contact area, which were obtained using the XSENSOR™ analysis software. For the static cushions, the average pressure, peak pressure and contact area were obtained from the one-frame pressure snapshot. For the dynamic cushion the peak pressure was selected as the greatest peak pressure measured during the 10-minute cycle period; the contact area and average pressure were obtained by averaging the contact area and average pressure per frame over the entire 10-minute cycle period. Data were exported into Microsoft Excel.

Muscle activation levels were converted from the time to the frequency domain using EMGworks 3.0®. The median value of the frequency spectrum of the data, referred to as the median frequency, was noted for each EMG data file. In doing so, the change in median frequency over the 8-hour session could be analyzed. This trend was analyzed for a shift to lower median frequencies as the session progressed, which was indicative of fatigue.

Oximeter data were exported into Microsoft Excel. A 5-minute average of the oxygen saturation level was calculated at every two-hour interval. This was then compared to the baseline values obtained at the start of the session and reported as a percent change.

For the Seated Comfort Survey, two weight cases were defined for each gender. These cases were lighter or heavier than 200 lbs for males and lighter or heavier than 145 lbs for females. These cases were defined in order to better identify relationships with seated pressure data. These data may relate to the amount of pressure at certain areas of the buttocks. By doing so, distinguishing between various seat pressure distributions and relating them to subjective results is possible. For the LPD section of the Seated Comfort Survey, the results of the LPD ratings for several body areas were combined for analysis (see Figure 7). The neck consisted of areas P, Q, R, S, and T. The back consisted of areas A – F and J – L. The arms and shoulders consisted of areas AA – EE, GG – KK and G, H, O, and M. The buttocks consisted of areas LL and SS. The upper legs consisted of areas MM and TT, and the legs combined all areas from the upper legs (MM, TT) to the feet (ZZ, RR).

Pressure mapping and oxygen saturation results were analyzed using the statistical software program JMP IN 5.1. One-way ANOVA was used to analyze the data. Post-

hoc Tukey HSD procedures were used to identify significant relationships. Seated Comfort Survey results were analyzed using the statistical software program Statistica version 7.1. An ANOVA was used to analyze the data for the ratings of the physical condition and the LPD. The subjects' gender (sex), body part area, weight case (light or heavy), time, and the four ejection seat cushions were independent variables. Effects were considered significant with $p \leq 0.05$. A Friedman ANOVA was used to analyze the seat ratings. Effects were considered significant with $p \leq 0.10$.

RESULTS

A total of 88 eight-hour test sessions on 9 females and 13 males were conducted at Wright State University under the supervision of Dr. David Reynolds, the WSU principal investigator of the study.

Pressure Measurement

Average Pressure

The average seat pan cushion pressure values and standard deviations for all four cushions are listed in Table 3 and shown in Figure 8. The highest average pressure over all 22 subjects was measured on Cushion D at 0.77 ± 0.10 psi followed by Cushion A at 0.64 ± 0.08 psi. The highest average pressure among the 9 female subjects and separately among the 13 male subjects was also measured on Cushion D at 0.70 ± 0.08 psi and 0.82 ± 0.09 psi, respectively.

Using one-way ANOVA and Tukey HSD analysis, it was concluded that there were no statistically significant differences between the means of the female average pressures for all four cushions. However, for the male average pressures a Tukey HSD indicated that the average pressure was significantly different between Cushions C and D ($p<0.001$).

Table 3. Average Pressure (psi) – mean and standard deviation

Cushion	All Subjects	Females	Males
A	0.64 ± 0.08	0.58 ± 0.07	0.69 ± 0.06
B	0.63 ± 0.08	0.57 ± 0.04	0.67 ± 0.07
C	0.59 ± 0.10	0.52 ± 0.12	0.64 ± 0.05
D	0.77 ± 0.10	0.70 ± 0.08	0.82 ± 0.09

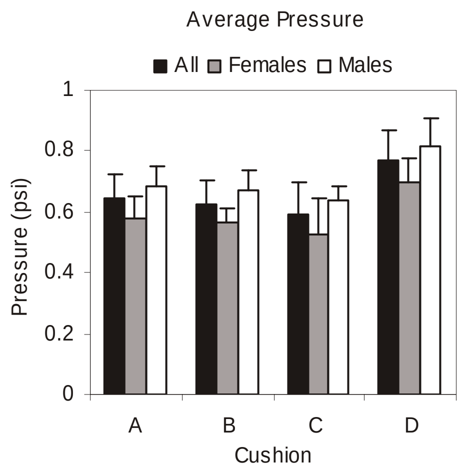


Figure 8. Average pressure

Peak Pressure

The peak seat pan cushion pressure values and standard deviations for all four cushions are listed in Table 4 and shown in Figure 9. The highest peak pressure over all 22 subjects was measured on Cushion D at 3.22 ± 0.28 psi, followed by Cushion B at 2.12 ± 0.91 psi. Cushion C exhibited the lowest peak pressure of 1.22 ± 0.38 for all the subjects. This was consistent across gender lines. The highest peak pressure within the subset of 9 female subjects was measured on Cushion D at 3.06 ± 0.30 psi, with the remaining cushions measuring between 1.04 and 1.68 psi. The highest peak pressure within the subset of 13 male subjects was also measured on Cushion D at 3.32 ± 0.22 psi, with the remaining cushions measuring between 1.34 and 2.42 psi.

Using one-way ANOVA and Tukey HSD analysis, it was concluded that Cushion C had a statistically lower average peak pressure than the other cushions for the male subjects. However, there were no statistically significant differences between Cushions A, B, and D. For the female peak pressures, the post-hoc analysis indicated that Cushion D was statistically significantly higher than Cushions A and C. Cushion B was not statistically different from the three other cushions. In addition, no statistical correlation was found between the measured peak pressures and the overall comfort responses over the 8-hour session.

Table 4. Peak Pressure (psi) – mean and standard deviation

Cushion	All Subjects	Females	Males
A	2.02 ± 0.84	1.57 ± 0.53	2.33 ± 0.89
B	2.12 ± 0.91	1.68 ± 0.66	2.42 ± 0.96
C	1.22 ± 0.38	1.04 ± 0.35	1.34 ± 0.35
D	3.22 ± 0.28	3.06 ± 0.30	3.32 ± 0.22

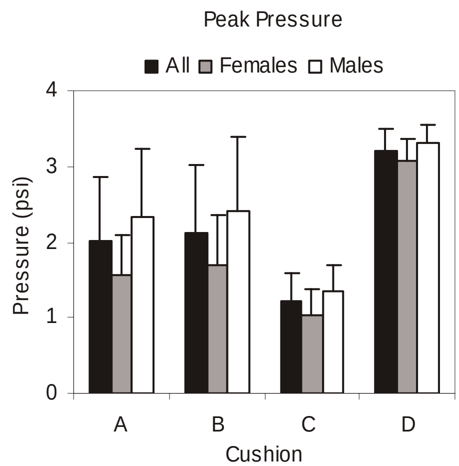


Figure 9. Peak pressure

Contact Area

The average seat pan cushion contact area values and standard deviations for all four cushions are listed in Table 5 and shown in Figure 10. The greatest average contact area for all 22 subjects was measured on Cushion B at 236.3 ± 19.37 in^2 followed by Cushion D at 227.16 ± 23.63 in^2. The greatest average contact area within the subset of 9 female subjects was also measured on Cushion B at 232.83 ± 12.91 in^2, with the remaining cushions ranging from 197.22 and 225.43 in^2. The greatest average contact area within the subset of 13 male subjects was also measured on Cushion B at 238.69 ± 23.03 in^2, followed closely by Cushion C which had a contact area of 238.12 ± 25.96 in^2.

Table 5. Contact Area (in^2) – mean and standard deviation

Cushion	All Subjects	Females	Males
A	216.56 ± 26.41	200.89 ± 19.47	227.40 ± 25.62
B	236.30 ± 19.37	232.83 ± 12.91	238.69 ± 23.03
C	221.38 ± 52.31	197.22 ± 71.13	238.12 ± 25.96
D	227.16 ± 23.63	225.43 ± 19.26	228.37 ± 26.94

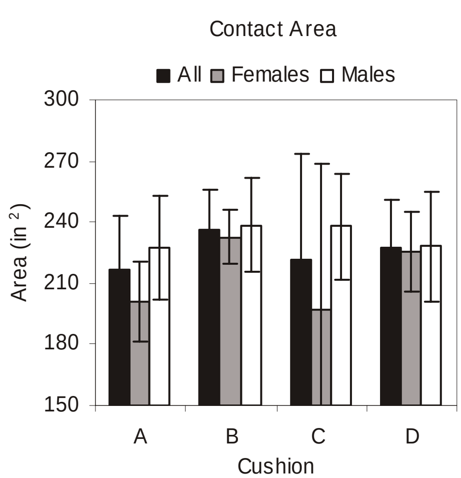


Figure 10. Contact area

Muscle Fatigue

As a measure of muscle fatigue, the median frequency of the EMG signal for the six monitored muscles was calculated for every 2-hour interval. These values were then compared to the base value at time zero to calculate the average percentage change in median frequency. The median frequency analyses of the lumbar muscles were contaminated due to the low signal-to-noise ratio. This essentially meant that these muscles exhibited no measurable activity. Therefore, these muscles are not included in the results.

The median frequency analyses indicated that fatigue over time was induced in the trapezius muscle for the three static cushions – Cushions A, B, and C (see Figure 11a). However, some degree of muscular recovery was present for Cushion D, the dynamic cushion, for both female and male subjects (see Figures 11b and 11c, respectively). Cushion A induced the highest level of fatigue for all subjects.

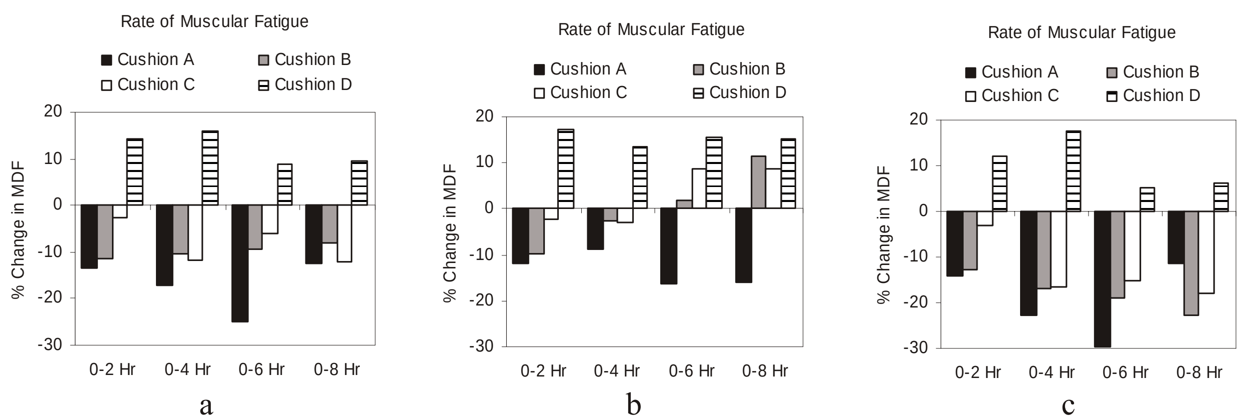


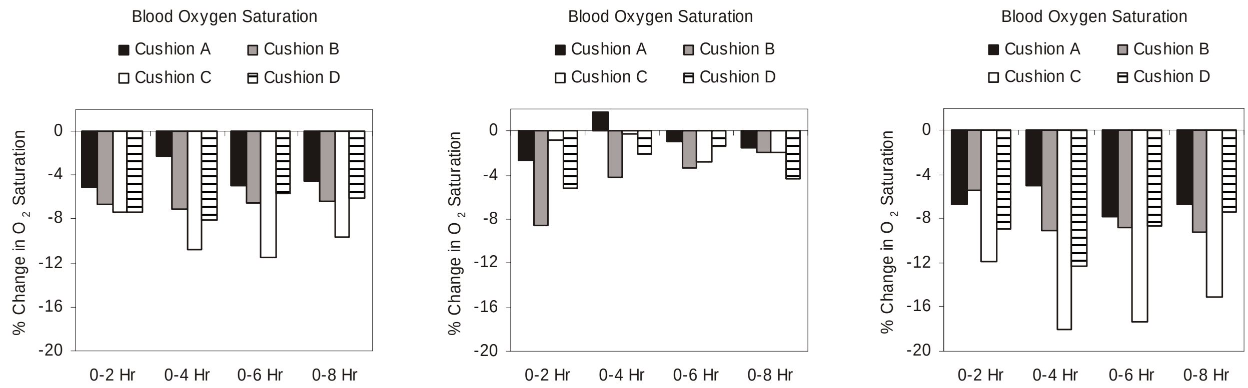
Figure 11. Rate of muscular fatigue for a) all subjects b) female subjects c) male subjects

Oxygen Saturation

An average of 5-minute periods of the lower extremity oxygen saturation data was calculated at every 2-hour interval and compared to baseline. Regardless of cushion, the general trend for all 22 subjects was a decrease in the oxygen saturation level over time (see Figure 12a). This trend remained consistent when the data are divided by gender, with the exception of a 1.66% increase from baseline for females on Cushion A (Figure 12b). Although there were no statistically significant differences between cushions for female subjects, males had a significantly higher decrease in oxygen saturation on Cushion C as compared with Cushions A and B (Figure 12c).

Using a one-way ANOVA and Tukey HSD analysis, it was concluded that no statistically significant differences between either cushion types or time intervals existed for oxygen saturation levels in female subjects. Cushion C elicited significantly different oxygen saturation levels from Cushions A and B in male subjects. However, no statistically

significant differences were found between the changes in blood oxygen saturation when analyzed against both cushion type and time interval.

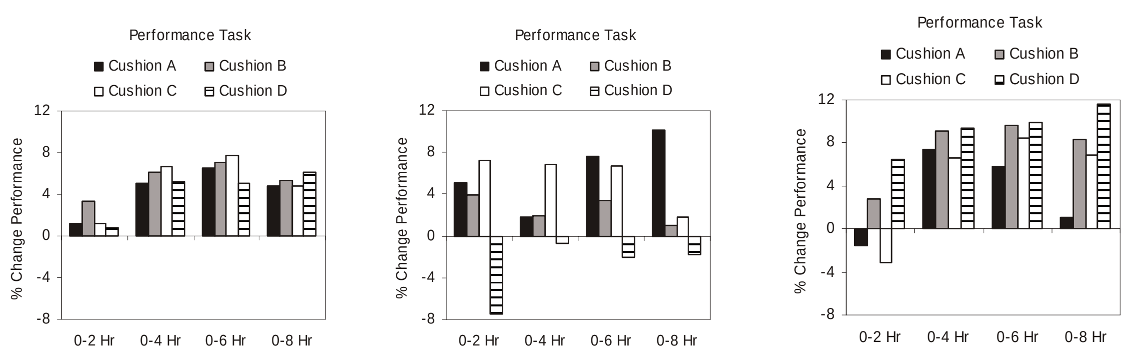


a b C

Figure 12. Change in O2 saturation for a) all subjects b) female subjects c) male subjects

Cognitive Task

The performance data from the SynWin task were analyzed to determine the percent improvement or degradation between the initial assessment at the beginning of each 8-hour test and the scores of every 2-hour assessment. The general trend for all 22 subjects was an improvement in performance between the initial assessment and each 2-hour assessment (see Figure 13a). For all cushions except Cushion D, subjects exhibited a steady increase in performance up to the 6-hour mark, after which there existed a slight decline. For Cushion D, the performance of the male subjects increased over the 8-hour session (see Figure 13c); however, the performance of the female subjects decreased throughout the 8 hours (see Figure 13b).



a b c

Figure 13. Change in performance for a) all subjects b) female subjects c) male subjects

Subjective Survey

Seated Comfort Survey
Subjects were divided by gender and then by weight case. Within the females, four subjects composed Weight Case 1 (<145 lbs) and five subjects composed Weight Case 2 (>145 lbs). Within the males, six subjects composed Weight Case 1 (<200 lbs) and seven subjects composed Weight Case 2 (>200 lbs).

Physical Condition
A significant effect ($p = 0.04$) was found for the physical condition of the subjects for the combined variables time, sex and weight case. The physical condition decreased over time, starting from good to OK (see Figure 14). The physical condition decreased the same amount for both males and females. Females started with a somewhat lower physical condition rating when compared to the male subjects. The second weight case within the female subjects started with a lower physical condition and had a lower rate of decrease in physical condition over the 8-hour session.

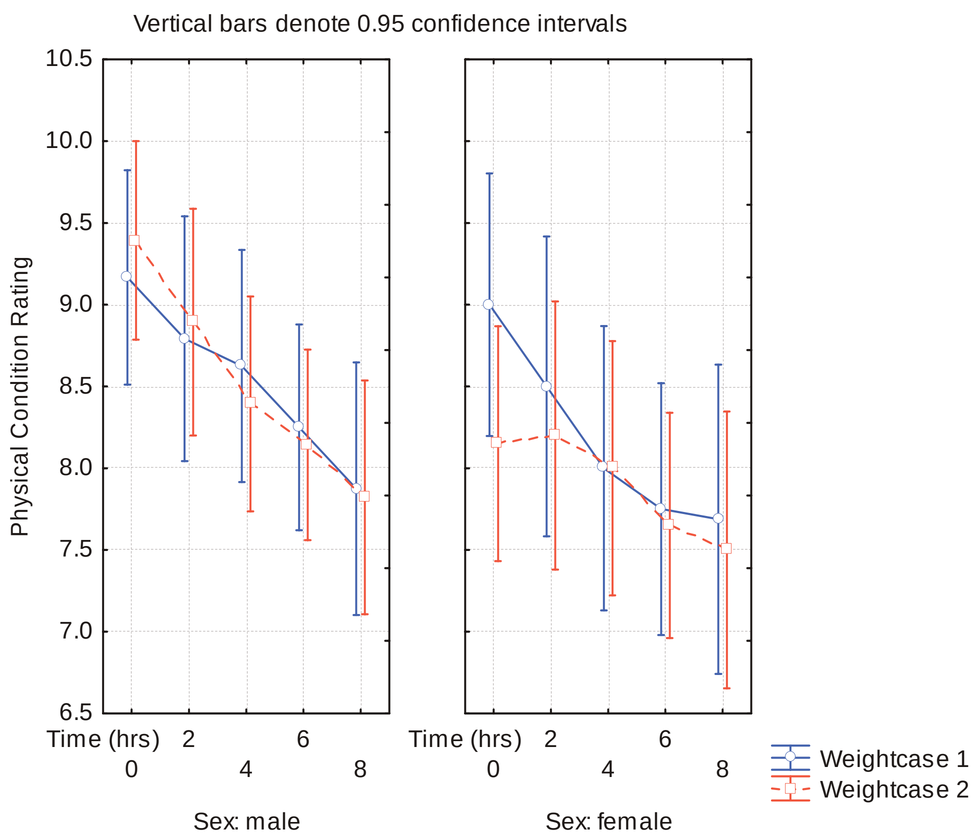


Figure 14. The subjects' (male and female) average physical condition (ranging from 0 (Bad) to 10 (great)) for both weight cases (light and heavy) at the start of the experiment and after intervals of 2 hours up to a total time of 8 hours

No difference in physical condition was found among the various seat cushions, indicating that all seat cushions performed similarly (see Figure 15).

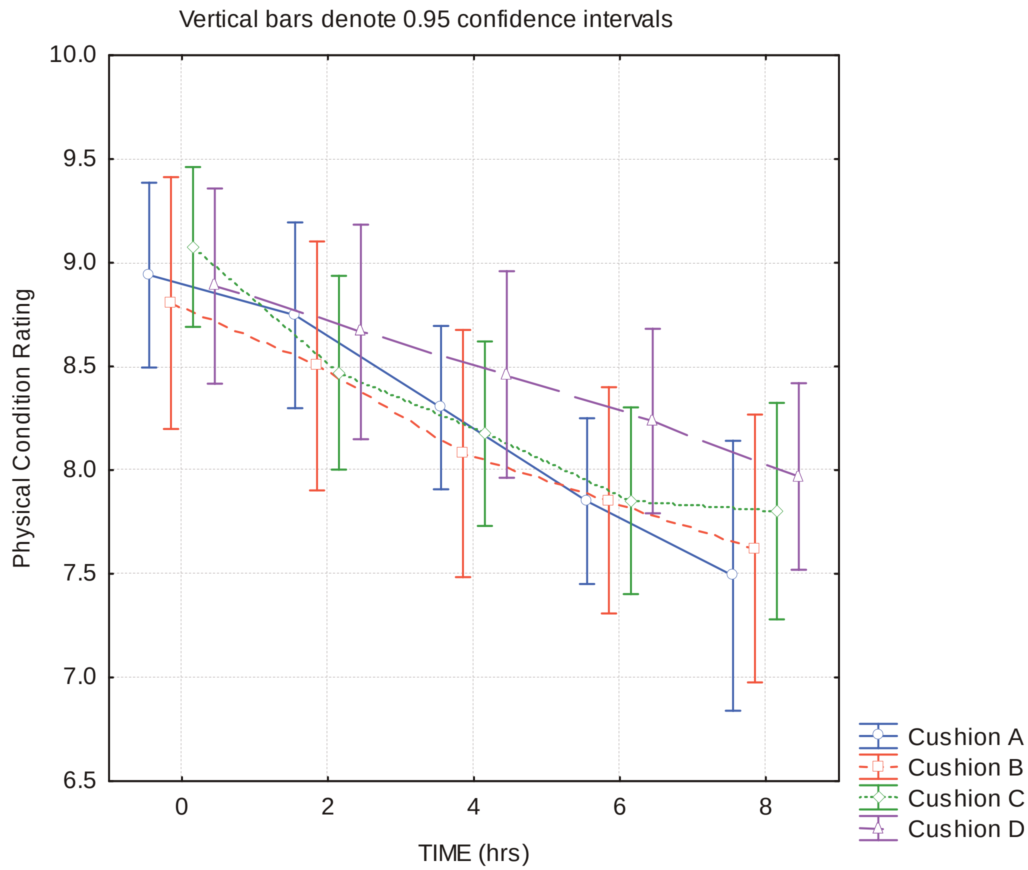


Figure 15. The subjects' (male and female) average physical condition (ranging from 0 (bad) to 10 (great)) for the four cushions at the start of the experiment and after intervals of 2 hours up to a total time of 8 hours

Local Postural Discomfort (LPD) Ratings

The Neck

The LPD ratings for the neck showed significant differences between males and females ($p = 0.05$) and over time ($p = 0.001$). Both males and females reported no discomfort at the start of the session (Figure16). However, the discomfort increased slightly during the 8-hour session for males and more for females, with an average increase of about 3 points (from no discomfort to moderate discomfort). Again, no difference in physical condition was found between the various seat cushions indicating that all seat cushions performed similarly.

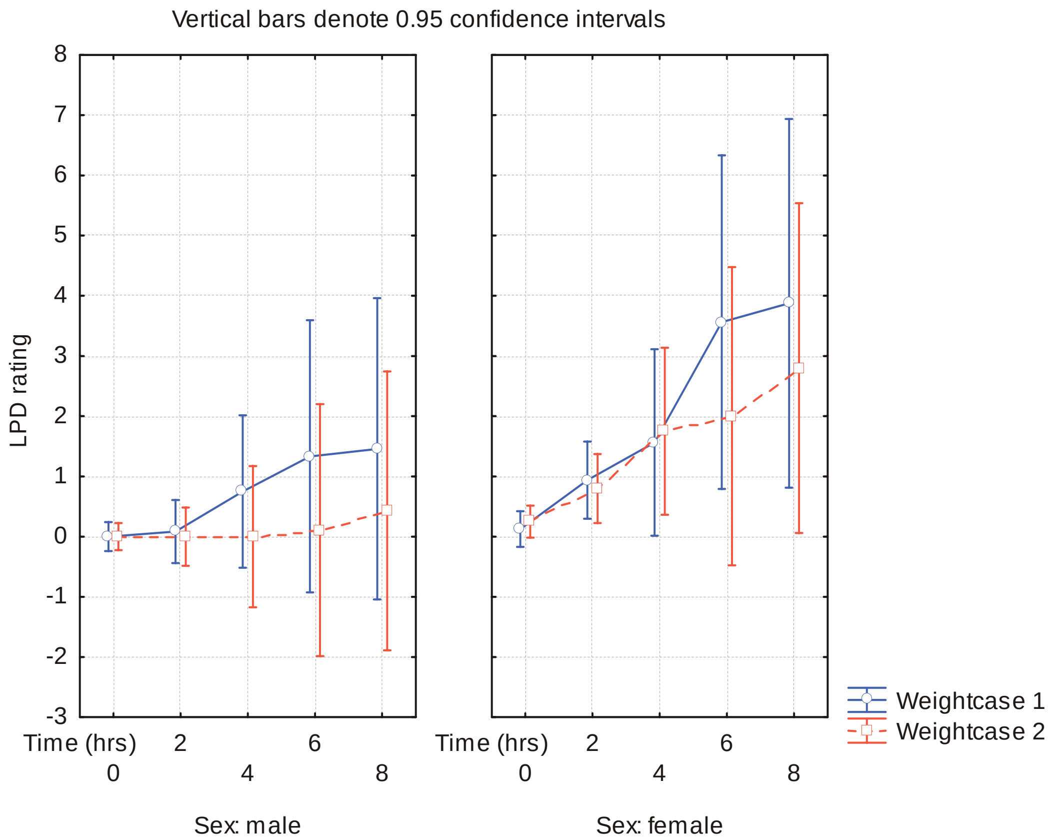


Figure 16. The subjects' (male and female) average LPD rating for the neck area (ranging from 0 (no discomfort) to 10 (maximum discomfort)) for the four cushions for both weight cases at the start of the experiment and after intervals of 2 hours up to a total time of 8 hours

The Shoulders, Arms and Knees

The subjects did not report any discomfort of the shoulders, arms and knees.

The Back

The LPD ratings for the back showed a significant difference in time ($p = 0.001$). Both males and females reported no discomfort at the start of the session (see Figure 17). However, the discomfort increased slightly during the 8-hour session for males and more for females, with an average increase of about 3 points (from no discomfort to moderate discomfort). Again, no difference in physical condition was found among the various seat cushions, indicating that all seat cushions performed similarly.

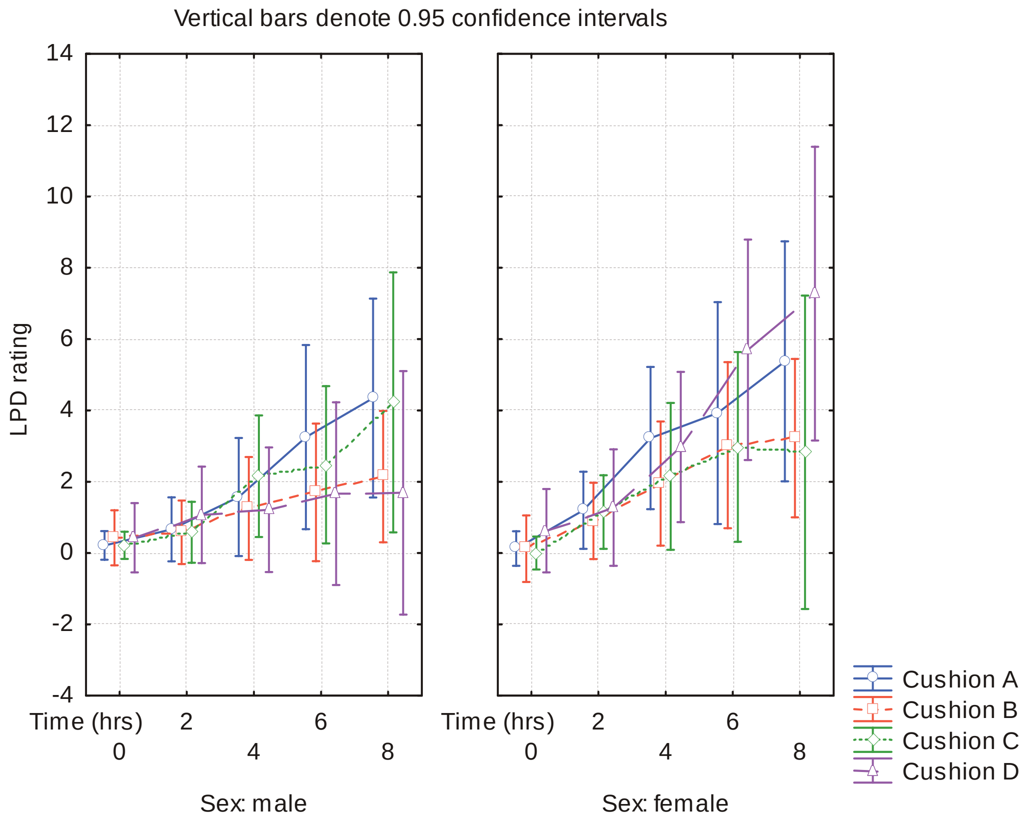


Figure 17. The subjects' (male and female) average LPD rating for the back area (ranging from 0 (no discomfort) to 10 (maximum discomfort) for the four cushions at the start of the experiment and after intervals of 2 hours up to a total time of 8 hours

The Buttocks

The LPD ratings for the buttocks showed a significant difference for time ($p = 0.001$), sex ($p = 0.05$) and weight ($p = 0.02$). Both males and females reported no discomfort at the start of the session (see Figure 18). However, the discomfort increased slightly during the 8-hour session for Male Weight Cases 1 and 2 and Female Weight Case 1. The discomfort increased almost to the level of 'somewhat strong discomfort' for Female Weight Case 1 with an average increase of about 4 points. Again, no difference in physical condition was found among the various seat cushions, indicating that all seat cushions performed similarly.

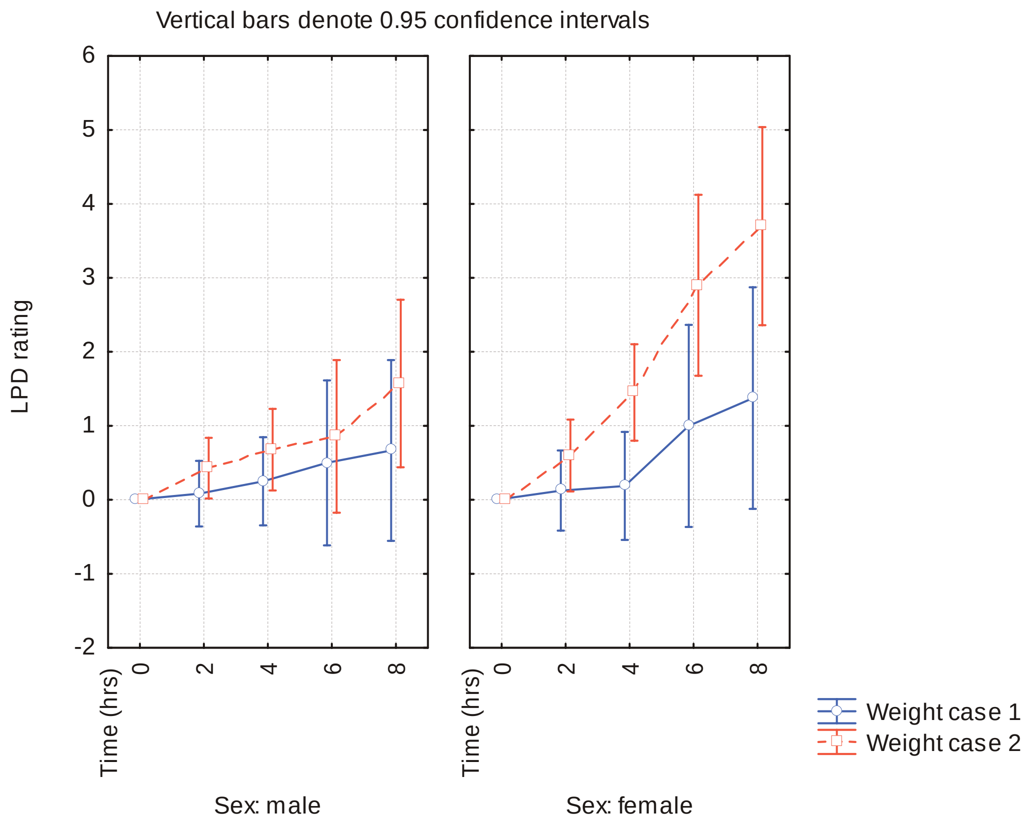


Figure 18. The subjects' (male and female) average physical condition (ranging from 0 (Bad) to 10 (great)) for both weight cases (light and heavy) at the start of the experiment and after intervals of 2 hours up to a total time of 8 hours

The Upper Legs

The LPD ratings for the upper legs showed a significant difference for time (p = 0.001) and for cushion type and sex combined (p = 0.04). Both males and females reported no discomfort at the start of the session (see Figure 19). However, the discomfort increased slightly during the 8-hour session for males and females. Cushions A and D caused more discomfort in time compared to Cushions B and C for females. A difference in comfort is found between the four cushion types.

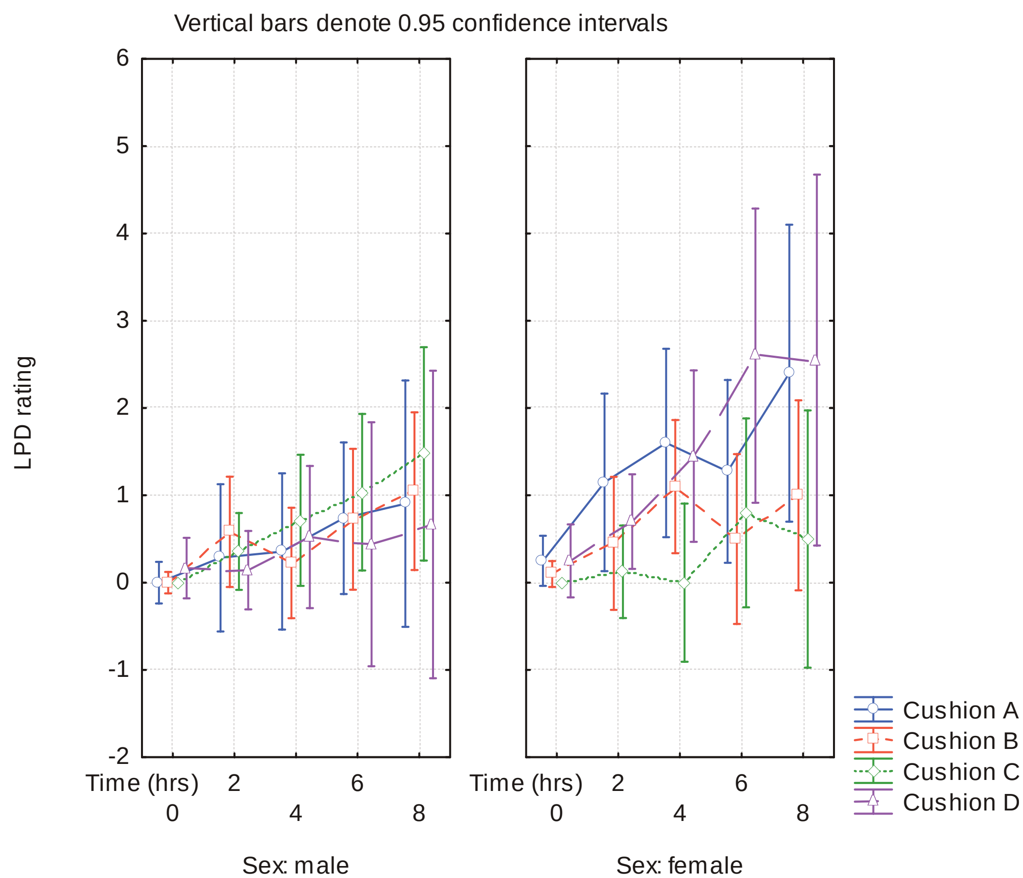


Figure 19. The subjects' (male and female) average LPD rating for the upper legs (ranging from 0 (no discomfort) to 10 (maximum discomfort) for the four cushions at the start of the experiment and after intervals of 2 hours up to a total time of 8 hours

General Seat Impressions

A significant preference (p = 0.0969) was found for the overall impression of all subjects. Cushions B and C, with a mean rating of 4 (the scale was bad (1) to good (5)) were found to be slightly more comfortable compared to Cushions A and D with a corresponding rating of 3.5.

Female subjects disliked the firmness of Cushions A and D; they were too firm. Again, Cushions B and C were preferred. No significant effects were found for the buttocks/lateral/sideways support or the thigh/legs support/comfort. A significant effect was found for the buttocks comfort for Female Weight Case 2: Cushions B and C were found to be more comfortable compared to Cushions A and D. Subjects did not feel differences in buttock/legs/thigh support and comfort for the different cushions. Only Female Weight Case 2 had a comfort preference for Cushions B and C.

Differences in comfort ratings were found for the backrest, despite the fact that the backrest did not change in properties. The configuration with Cushion B was preferred by the subjects (both male and female) for comfort of the lower, middle and upper back. This configuration gave the highest comfort ratings and the best 'firmness' ratings. The subjects disliked the firmness of Cushions A and D; they were too firm. Cushions B and C were preferred. Cushion A gave the lowest comfort ratings for the lower, middle and upper back. No differences were found in comfort rankings between males/females and weight cases. The comfort ratings for the lower back gave the most significant differences for both sexes and weight cases.

From the Seated Comfort Survey it was found that the LPD measurements gave only comfort differences for Female Weight Case 2. This group of subjects preferred Cushions B and C. This group also reported the highest amount of discomfort. The seat comfort ratings showed that Cushions B and C were preferred by all subjects, especially for the backrest. Cushions A and D gave the lowest comfort ratings.

<u>End-of-Day Comfort Survey</u>

The End-of-Day Comfort Survey was administered after the 8-hour session was complete, immediately after the subject had stood up from the ejection seat. As with the Seated Comfort Survey, females reported the highest discomfort for Cushion D for both the buttocks and the thighs. The cushion that the females found the most comfortable, Cushion C, was the one that males rated as the most uncomfortable for both the buttocks (Figure 20a) and the thighs (Figure 20b).

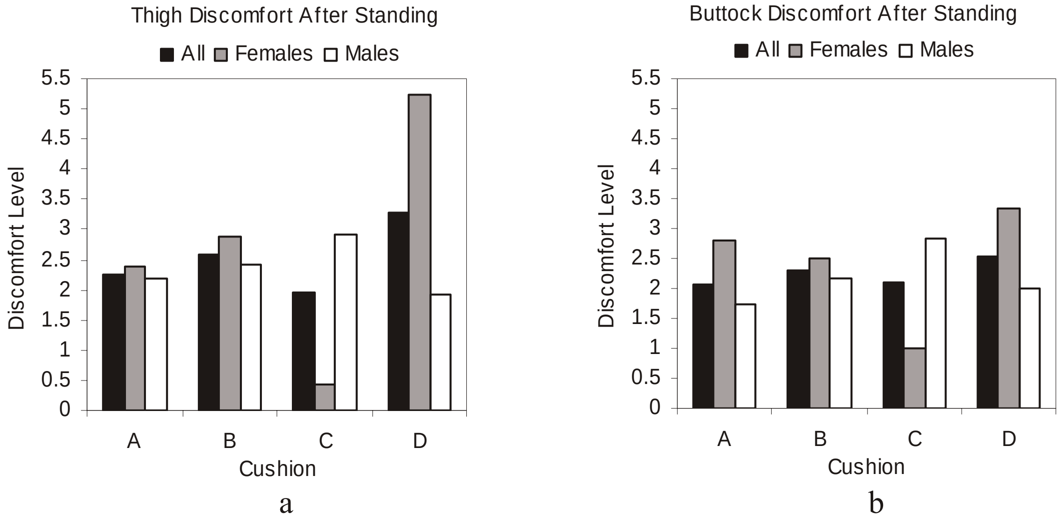


Figure 20. Discomfort Levels after Standing for a) the thighs b) the buttocks

DISCUSSION

Current operational and prototype cushions were tested using objective and subjective methods to determine comfort characteristics. Peak pressure, muscle fatigue, lower extremity oxygen saturation, performance scores, and survey data were collected over the course of 8-hour sit tests.

Peak pressure was measured using the XSENSOR™ X2 pressure measurement system. As in the cushion evaluation conducted by Stubbs *et al*. [2], it was expected that cushions with the lowest peak pressure points would show similar positive characteristics in other subjective and objective tests and that cushions with the highest peak pressure points would show similar negative characteristics in the other tests. For the static cushions, this proved to be the case for the correlation between average peak pressure and subjective discomfort survey ratings for the buttocks and thighs. Cushion A, the current operational ACES II cushion, exhibited high peak pressure values and was rated as the least comfortable in buttocks and thigh discomfort among the static cushions. Cushion C, the Stimulite/Confor™ blend cushion, exhibited the lowest average peak pressure as well as the lowest buttocks and thigh discomfort rating while seated among all cushions for both female and male subjects. The dynamic cushion did not follow this same trend. Cushion D, the ErgoDynamic™ cushion, elicited the highest peak pressure among all cushions for all subjects, but was not rated as the most uncomfortable by males. Females, on the other hand, reported very high levels of seated and end-of-day discomfort with Cushion D. Positive correlation was also noted between the performance task data and the highest peak pressure for the static cushions, which is in agreement with the previous study [2]. Among the static cushions, Cushion C showed the greatest improvement in the composite task score over 8 hours. The dynamic cushion, Cushion D, showed the greatest improvement of all cushions for the male subjects, but showed a decrement in scores throughout the 8-hour session for females. The results of the performance task suggest that static cushion comfort does not have a negative impact on subject performance;

however, low dynamic cushion comfort may be detrimental to performance. The wide difference between genders on the comfort responses to the dynamic cushion is probably in part due to the pressure exerted by the cushion and the changes over time. The pressure changes may be providing a level of relief to the males but not to the females. Comfort of dynamic cushions may be highly dependent upon gender-related anthropometric variations and this should be further investigated.

The three static cushions also elicited similar responses in levels of trapezius muscle fatigue. Trapezius muscle fatigue was exhibited throughout the 8-hour session for male subjects for all three static cushions. Cushion A induced the highest rate of muscle fatigue for both males and females. Cushion A is the only cushion that fatigued the females throughout the entire 8-hour session. Cushions B and C were fatiguing up to the 4-hour mark, after which recovery was present. The dynamic cushion elicited a unique response for both males and females due to the fact that no fatigue, and potentially recovery, occurred at every 2-hour interval. No measurable activity was present for the lumbar muscles. This may be due to the lack of constraints placed on the assumed posture of the subjects. Restricting the motion, as is typical in aircraft such as the F-16, should induce fatigue due to the low level but constant activity that would be required of the lumbar muscles to maintain a restricted posture. More realistic aircraft scenarios with appropriate mobility restraints will be investigated in future studies. Restraining the posture will not only affect fatigue in the lumbar musculature, but will also affect the trapezius muscles because these muscles are more indicative of head and neck positioning, which can be influenced by the overall body position.

Although minimal changes of oxygen saturation and no differences between cushions were found for female subjects, males exhibited significantly decreased levels of oxygen saturation for all cushions, especially for Cushion C. This cushion, although eliciting the lowest average peak pressure, had the highest levels of discomfort in the buttocks and thighs for the male subjects after standing. Due to the low pressures, male subjects may have felt that minimal movement was necessary to maintain comfort. This is supported by the low levels of oxygen saturation measured in male subjects for this cushion. This illuminates the necessity for additional objective measures of comfort other than the traditional measure of seated pressures. Although pressure issues are of utmost importance, if a cushion is composed of such materials that little to no movement is necessary to remain comfortable, this may prove to be detrimental because motion and maintaining proper blood flow are necessary to mitigate long-term effects such as the discomfort that the male subjects felt after standing. An automated dynamic cushion may help to alleviate this problem because motion under the buttocks will be forced and blood circulation will be maintained. It must be noted that monitoring oxygen saturation in the lower extremities is a relatively new modality for determining blood flow and pooling patterns, and oximeter data collection and processing techniques must be further investigated.

The difference in cushion properties and preferences between genders was a finding of interest in this study and will be examined in future studies. The differences could potentially be related to anthropometric and weight distribution variations between genders and their respective interactions with varying cushion materials. Additionally, a

mock-up of the entire F-16 cockpit, including the ejection seat, rudder pedals and controls, would more realistically simulate the biomechanical effects of the postural limitations due to the restricted space in terms of muscular fatigue and blood pooling. And, for muscular fatigue, monitoring isometric muscle activity while exerting a known force will ensure median frequency fatigue calculations are done on signals collected during isometric contractions. Future work will be conducted that places this physical demand on the subject and will better simulate the biomechanical response to the ejection seat cushion.

CONCLUSION

In total, 88 eight-hour test sessions were completed. No incidence of injuries occurred in any subject at any time during this study. As in previous findings, peak pressure correlated well with comfort ratings for the static cushions where higher pressures elicited higher discomfort. However, low peak pressures may cause less fidgeting and promote blood pooling, which can induce discomfort after a long period of sitting. Static cushions also seem to have no benefit in muscle fatigue mitigation. Due to the concern with long periods of static sitting causing deep vein thrombosis and pressure sores, investigations of dynamic cushions must continue. Dynamic cushions indicated that there may be trade-offs in performance and fatigue mitigation, but further studies must be done to understand the implications of dynamic stimulation on both female and male operators. These findings will be used in developing cushion design guidelines that will maximize performance and comfort without jeopardizing ejection safety.

REFERENCES

1. Pint, S.M., Pellettiere, J.A., Nguyen, C., "Development of Objective Test Methods for Determination of Ejection Seat Cushion Comfort," SAFE Association Conference Proceedings, 2002.

2. Stubbs, J., Pellettiere, J.A., and Pint, S.M. "Quantitative Method for Determining Cushion Comfort," Paper # 2005-01-1005, Society of Automotive Engineers (SAE), 2005.

3. Cohen, D., "An Objective Measure of Seat Comfort," *Aviation Space Environmental Medicine*, 69:410-4, 1998.

4. Hearon, B.F. and Brinkley, J.W., "Effect of Seat Cushions on Human Response to +Gz Impact," *Aviation Space Environmental Medicine*, 57:113-21, 1986.

5. Severance, C.M., "B-2 Aircrew Seat Comfort Cushion Design and Development," Northrop Grumman Corporation, Palmdale, CA, 25-32, SAFE Association Symposium Proceedings, 1997.

6. Pint, S.M., Internal Memorandum, ACES II Seat Cushion Comfort Interview with LtCol Lex Brown, AFRL/HEC, 2 Aug 99.

7. VanIngen-Dunn, C. and Richards, M.K., "Feasibility of Reducing Incidence of Low Back Pain in Helicopter Pilots Using Improved Crewseat Cushions," AL-SR-1991-0009, Armstrong Laboratory, Wright-Patterson AFB OH, 1992.

8. Perry, C.E., "Evaluation of a Proposed B-2 Seat Cushion by +Gz Impact," AL/CF-TR-1997-0112, Armstrong Laboratory, Wright Patterson AFB OH, 1997.

9. Perry, C.E., Nguyen, T.Q., and Pint, S.M., "Evaluation of Proposed Seat Cushions to Vertical Impact," SAFE Association Symposium Proceedings, Reno NV, 2000.

10. Cantor, A., "Live Qualification of the Lumbar Pad and Pulsating Seat Cushion for the S-3A Escape System," NADC-74031-40, Naval Air Development Center (NADC), Warminster PA, 1974.

11. Ferguson-Pell, M.W. and Cardi, M., "Pressure Mapping Systems for Seating and Positioning Applications: Technical and Clinical Performance," Helen Hayes Hospital, Center for Rehab Technology, RESNA International '92, 219-221, 1992.

12. Ferguson-Pell, M.W. and Cardi, M., "Pressure Mapping Systems," Team Rehab Report, 27-32, 1992.